Improving SHAW long-term soil moisture prediction for continuous wheat rotations, Alberta, Canada

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[1]Semiarid Prairie Agricultural Research Centre, Agriculture and Agri-Food Canada. Box 1030, Swift Current, Saskatchewan, Canada S9H 3X2 (e-mail: hong.wang@agr.gc.ca); [2]USDA Agricultural Research Service, Northwest Watershed Research Center, Boise, ID 83712, USA; and [3]Alberta Agriculture, Food and Rural Development, Edmonton, Alberta, Canada T6H 5T6. *Received 11 November 2008, accepted 24 September 2009.*

Wang, H., Flerchinger, G. N., Lemke, R., Brandt, K., Goddard, T. and Sprout, C. 2010. **Improving SHAW long-term soil moisture prediction for continuous wheat rotations, Alberta, Canada**. Can. J. Soil Sci. **90**: 37–53. The Decision Support System for Agrotechnology Transfer-Cropping System Model (DSSAT-CSM) is a widely used modeling package that often simulates wheat yield and biomass well. However, some previous studies reported that its simulation on soil moisture was not always satisfactory. On the other hand, the Simultaneous Heat and Water (SHAW) model, a more sophisticated, hourly time step soil microclimate model, needs inputs of plant canopy development over time, which are difficult to measure in the field especially for a long-term period (longer than a year). The SHAW model also needs information on surface residue, but treats them as constants. In reality, however, surface residue changes continuously under the effect of tillage, rotation and environment. We therefore proposed to use DSSAT-CSM to simulate dynamics of plant growth and soil surface residue for input into SHAW, so as to predict soil water dynamics. This approach was tested using three conventionally tilled wheat rotations (continuous wheat, wheat-fallow and wheat-wheat-fallow) of a long-term cropping systems study located on a Thin Black Chernozemic clay loam near Three Hills, Alberta, Canada. Results showed that DSSAT-CSM often overestimated the drying of the surface layers in wheat rotations, but consistently overestimated soil moisture in the deep soil. This is likely due to the underestimation of root water extraction despite model predictions that the root system reached 80 cm. Among the eight growth/residue parameters simulated by DSSAT-CSM, root depth, leaf area index and residue thickness are the most influential characteristics on the simulation of soil moisture by SHAW. The SHAW model using DSSAT-CSM-simulated information significantly improved prediction of soil moisture at different depths and total soil water at 0–120 cm in all rotations with different phases compared with that simulated by DSSAT-CSM.

Key words: Soil moisture, modeling, Decision Support System for Agrotechnology Transfer-Cropping System Model, Simultaneous Heat and Water Model

Wang, H., Flerchinger, G. N., Lemke, R., Brandt, K., Goddard, T. et Sprout, C. 2010. **Amélioration du modèle SHAW pour la prévision à long terme de la teneur en eau du sol avec la monoculture du blé en Alberta (Canada).** Can. J. Soil Sci. **90**: 37–53. Le *Decision Support System for Agrotechnology Transfer-Cropping System Model* (DSSAT-CSM) est un modèle largement utilisé qui simule souvent bien le rendement et la biomasse du blé. Quelques études antérieures rapportaient néanmoins que ce modèle ne simule pas toujours de manière satisfaisante la teneur en eau du sol. De son côté, le modèle SHAW (*Simultaneous Heat and Water*), qui simule de manière plus complexe le microclimat du sol d'heure en heure, a besoin de données sur le développement de la végétation dans le temps, données difficiles à obtenir sur le terrain, surtout sur de longues périodes (plus d'un an). Le modèle SHAW nécessite aussi des données sur les résidus de surface, qu'il traite comme une constante. En réalité cependant, ces résidus évoluent constamment avec le travail du sol, les assolements et l'environnement. C'est pourquoi les auteurs proposent de simuler la dynamique de la croissance des plantes et les résidus de surface avec le DSSAT-CSM, puis d'utiliser les résultats avec le modèle SHAW afin de prévoir la dynamique de l'eau. Cette approche a été testée sur trois assolements typiques du blé (monoculture, blé-jachère et blé-blé-jachère) dans le cadre d'une étude de longue haleine sur les systèmes agricoles, dans une zone de minces loams argileux de type tchernoziom noir, près de Three Hills, en Alberta (Canada). Les résultats indiquent que le DSSAT-CSM surestime souvent l'assèchement des couches superficielles dans les assolements de blé et surestime toujours la teneur en eau du sol en profondeur. On le doit sans doute à une sous-estimation de la quantité d'eau absorbée par le système racinaire, bien que le modèle prévoie un enracinement à 80 cm de profondeur. Sur les huit paramètres associés à la croissance et aux résidus du DSSAT-CSM, la profondeur des racines, l'indice foliaire et l'épaisseur de la couche de résidus exercent le plus d'influence sur la simulation de la teneur en eau du sol par le modèle SHAW. Utiliser les données du DSSAT-CSM améliore sensiblement la teneur en eau du sol prévue par le modèle SHAW à diverses profondeurs, ainsi que la teneur en eau totale entre 0 et 120 cm, pour tous les assolements à différentes phases, comparativement aux résultats obtenus avec le DSSAT-CSM.

Abbreviations: DSSAT-CSM, Decision Support System for Agrotechnology Transfer-Cropping System Model; **SHAW**, Simultaneous Heat and Water; **CCC**, concordance correlation coefficient; ***F* (LOFIT)**, *F* value for the lack of fit.

Mots clés: Teneur en eau du sol, modélisation, DSSAT-CSM, SHAW

Simulation of soil moisture is an important component in ecosystem modeling since it is involved with global energy and water balance and biophysical processes in the system. In wheat (*Triticum aestivum* L.), soil moisture is among the most important factors influencing growth (Merrill et al. 1996), developments of pests (Sehgal et al. 2001), diseases (Gill et al. 2001), weeds (Blackshaw 1991), the microbial transformation of soil organic matter (Hoyle et al. 2006) and environmental contaminants (Röver et al. 1998). The Decision Support System for Agrotechnology Transfer-Cropping System Model (DSSAT-CSM) is a widely used modeling package which was successful for many different applications, such as plant production estimates, land use planning, prediction of climate change impact on agriculture and analysis of environmental impact of agricultural activities (Jones et al. 2003; Kalra et al. 2007). The model has simulated wheat yield and biomass generally well in many environments including western Canada (Pei and Ripley 1988; Moulin and Beckie 1993; Touré et al. 1995; Beckie et al. 1995; Chipanshi et al. 1997, 1999). We are currently using DSSAT-CSM to predict impacts of climate change on the production of cereal crops in western Canada. The simulation of soil moisture by DSSAT-CSM, however, was not very successful in some studies (Beckie et al. 1995; Hasegawa et al. 2000; Ines et al. 2001; Eitzinger et al. 2004; Casanova et al. 2006). For example, Beckie et al. (1995) found that CERES, a module of DSSAT-CSM, overestimated soil moisture in the top 0.3-m layer of soil at Melfort, SK. In a Mediterranean climate, Hasegawa et al. (2000) reported that CERES overestimated the drying of the surface layers in wheat rotations. Casanova et al. (2006) pointed out that the CERES model simulates moisture at daily time steps, while the hydrological changes near the soil surface (0–5 cm) occur at much shorter time steps, making it challenging to compare modeled and observed near surface soil moisture. Therefore, it is desirable to integrate a more sophisticated physically based soil microclimate model into DSSAT-CSM to improve the simulation performance of DSSAT-CSM.

Although there are several soil microclimate models operating on an hourly time step (e.g., DAISY, Hansen et al. 1990; SOIL, Jansson 1991; ENWATBAL, Evett and Lascano 1993; ecosys, Grant 1995; 2DSOIL, Timlin et al. 1996; SHAW, Eitzinger et al. 2000; and SABAE-HW, Loukili et al. 2008), we chose the Simultaneous Heat and Water model (SHAW) because: (1) it was developed specifically to address effects of tillage, residue and vegetation canopy on soil freezing, thawing and runoff from frozen soils (Flerchinger and Saxton 1989; Flerchinger and Pierson 1991) and (2) it has been tested successfully for simulating heat movement, evapotranspiration, temperature, moisture and freezing depth of the soil over a wide range of conditions (Flerchinger and Pierson 1991; Flerchinger et al. 2003; Flerchinger and Hardegree 2004; Preston and McBride 2004; Huang and Gallich 2006; Fallow et al. 2007), especially in cold regions (Kennedy and Sharratt 1998; DeGaetano et al. 2001).

The SHAW model needs inputs of plant canopy development over time, which are difficult to measure in the field especially for a long-term period (longer than a year). The model also needs surface residue information, but treats them as constants. In reality, surface residue changes continuously under the effect of tillage, rotation and environment (Curtin et al. 2000). We hypothesize that the dynamics of canopy and surface residue characteristics simulated by DSSAT-CSM could be used for providing inputs to SHAW. The objective of this study was to test if the long-term dynamics of soil moisture can be predicted by SHAW using canopy and residue information estimated by DSSAT-CSM.

MATERIALS AND METHODS

The Experiment

Data for model testing were collected from a long-term cropping systems experiment located on a Thin Black Chernozemic clay loam near Three Hills, Alberta,

Table 1. Soil characteristics for each horizon

Horizon	Depth (cm)	Bulk density (g cm^{-3})	Sand (%)	Silt (%)	Clay (%)	pH^{z}	Organic C (%)
Ap	0–10	1.21	30	36	35	4.9	3.65
Bm	10–23	1.34	27	35	38	5.1	2.07
Aej	23–28	1.34	31	45	24	5.5	1.38
2Btnj	28–43	1.38	21	27	52	6.8	1.15
2Btku	43–75	1.38	25	16	59	8.0	0.93
2Ck	75–80	1.40	25	28	47	7.9	0.71
2Cks	80–110	1.50	23	18	59	7.9	0.62

^{z}Measured using calcium chloride solution.

Canada (lat. 51°42′N, long. 113°13′W, altitude 907 m). Soil characteristics collected for each horizon in 1994 are summarized in Table 1. The details of the study were described by Wang et al. (2007a). Briefly, the experiment was initiated in 1991 with the whole area seeded to canola, then nine different crop rotation treatments began in 1992 and continued to 2006 [continuous wheat, wheat-fallow, wheat-wheat-fallow, peas-wheat-fallow, canola-barley-peas-wheat, wheat-green manure (peas), wheat-peas-oat silage-fall rye, grass, and the mixture of alfalfa and grass]. All phases of each rotation were present each year. The experimental design was a randomized complete block with three replications. Since the fall of 1994 each treatment was split into two tillage methods: conventional and no-till with a 4.5×15 m area for each split plot. The conventional system usually received pre-seed and post-harvest tillage operations during the cropping year and some tillage operations during the fallow year, which are listed in detail in Table 2.

In this paper we report the results of conventional till treatments of continuous wheat, wheat-fallow and wheat-wheat-fallow. Varieties of Canada Western Red Spring (CWRS) wheat (*Triticum aestivum* L.) [Bluesky in 1998 (Clarke et al. 1994) and AC Barrie in 1999 to 2005 (McCaig et al. 1996)] were seeded with a low disturbance John Deere 752 double disc drill equipped with 16 openers on a 19-cm spacing. At seeding, 67 kg N ha^{-1} of urea [$(NH_2)_2CO$] (46–0–0) was banded at a 6-cm depth and 15 kg P ha^{-1} of monoammonium phosphate [$NH_4H_2PO_4$] (11–52–0) was placed 4 cm deep with the seed using the drill. From 1998 onwards, above-ground biomass was determined at full maturity by hand harvesting a random 1 m^2 area within each plot and grain yield was determined with a Wintersteiger plot combine, which harvested a 1.7×7 m strip through the middle of the southern part of the plots. In the fall of 2006 (Oct. 06–07), just after harvest and before tillage, surface residue dry weight was measured from continuous wheat and wheat phases of wheat-fallow and wheat-wheat-fallow. Residue samples were collected and weighed from two areas of 0.1 m^2 from each plot.

From 1997 to 2006 soil water content before seeding at depths of 0–15, 15–30, 30–60, 60–90, and 90–120 cm was obtained by the gravimetric method yearly from each plot. On 1998 Sep. 09 an extra measurement was conducted at above-mentioned depths (11 measurements in total). Additional measurements at 0–15 cm were taken in the growing seasons of 2000 (eight) and 2001 (three) for the continuous wheat and wheat-fallow rotations (22 measurements in total). From 2001 to 2005, an impedance-based sensor, ML2 Theta probe (Delta-T Devices Ltd., Cambridge, UK) was used to measure moisture at 0–6 cm usually once a week in the growing seasons from each plot of rotations of continuous wheat and wheat-fallow.

Table 2. Cropping phase and tillage time since the start of the rotations in 1992[z]

Rotation	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004[y]	2005	2006[y]
Continuous wheat	W (1, 2)[x]	W (1, 2)	W (1, 2)	W (1, 2)	W (1, 2)	W (1, 2)	W (2, 2)	W (1, 3)	W (1, 2)	W (1, 1)	W (1, 1)	W (1, 1)	W (1, 0)	W (1, 1)	W (1, 0)
Wheat-fallow-1	W (1, 2)	F (4)[w]	W (1, 2)	F (4)	W (1, 2)	F (4)	W (2, 2)	F (6)	W (1, 2)	F (3)	W (1, 1)	F (2)	W (1, 0)	F (2)	W (1, 0)
Wheat-fallow-2	F (4)	W (1, 2)	F (4)	W (1, 2)	F (4)	W (1, 2)	F (4)	W (1, 3)	F (4)	W (1, 1)	F (4)	W (1, 1)	F (3)	W (1, 1)	F (1)
Wheat-wheat-fallow-1	W (1, 2)	W (1, 2)	F (4)	W (1, 2)	W (1, 2)	F (4)	W (2, 2)	W (1, 3)	F (4)	W (1, 1)	W (1, 1)	F (2)	W (1, 0)	W (1, 1)	F (1)
Wheat-wheat-fallow-2	W (1, 2)	F (4)	W (1, 2)	W (1, 2)	F (4)	W (1, 2)	W (2, 2)	F (6)	W (1, 2)	W (1, 1)	F (4)	W (1, 1)	W (1, 0)	F (2)	W (1, 0)
Wheat-wheat-fallow-3	F (4)	W (1, 2)	W (1, 2)	F (4)	W (1, 2)	W (1, 2)	F (4)	W (1, 3)	W (1, 2)	F (3)	W (1, 1)	W (1, 1)	F (3)	W (1, 1)	W (1, 0)

[z]W, spring wheat; F, fallow.
[y]No tillage was done after harvest because the surface moisture was too high.
[x]Numbers in parentheses after W are tillage times. The first number is pre-seeding tillage and the second number is post-harvest tillage.
[w]Numbers in parentheses after F are tillage times in the fallow year.

Table 3. Direct, indirect and total effects of DSSAT-CSM-simulated leaf area index, root depth and residue thickness on SHAW-simulated soil moisture at depths of 5, 10, 20, 40 and 100 cm[z]

	Leaf area index	Root depth	Residue thickness	Total effect
5 cm				
Leaf area index	**−0.16 (−0.45, 0.09)**	*−0.39*	*0.24*	−0.30*
Root depth	*−0.09*	**−0.65 (−0.85, −0.42)**	*0.19*	−0.55***
Residue thickness	*−0.06*	*−0.19*	**0.65 (0.51, 0.81)**	0.40**
10 cm				
Leaf area index	**−0.20 (−0.48, 0.02)**	*−0.42*	*0.16*	−0.44**
Root depth	*−0.12*	**−0.71 (−0.92, −0.50)**	*0.14*	−0.68***
Residue thickness	*−0.07*	*−0.21*	**0.49 (0.37, 0.64)**	0.21
20 cm				
Leaf area index	**−0.15 (−0.44, 0.09)**	*−0.42*	*0.17*	−0.41**
Root depth	*−0.09*	**−0.71 (−0.91, −0.50)**	*0.13*	−0.67***
Residue thickness	*−0.06*	*−0.21*	**0.45 (0.32, 0.60)**	0.19
40 cm				
Leaf area index	**−0.19 (−0.48, 0.04)**	*−0.41*	*0.16*	−0.44**
Root depth	*−0.11*	**−0.70 (−0.90, −0.48)**	*0.13*	−0.68***
Residue thickness	*−0.07*	*−0.20*	**0.44 (0.31, 0.59)**	0.17
100 cm				
Leaf area index	**−0.24 (−0.56, 0.00)**	*−0.37*	*0.18*	−0.43**
Root depth	*−0.14*	**−0.63 (−0.84, −0.36)**	*0.14*	−0.63***
Residue thickness	*−0.09*	*−0.18*	**0.49 (0.34, 0.65)**	0.22

[z]The SHAW model was run using 48 pairs of DSSAT 10-yr growth and residue outputs, which were created by varying fertilizer rate, irrigation, rotation and tillage. Bold numbers are direct effects with bootstrap 95% confidence intervals and italic numbers are indirect effects.
*, **, *** Significant at 0.05, 0.01 and 0.001 probability level, respectively.

The DSSAT-CSM Model

The DSSAT-CSM package (Version 4.0) is a collection of independent programs including 16 crop models and a set of modules for the simulation of soil temperature, water, carbon and nitrogen balances. It also has tools and utility programs for managing data on soil, climate, genetics, crops, economics, and pests; and has application and analysis programs.

Model Description

The plant life cycle in the wheat growth module of DSSAT-CSM is divided into several stages. Rate of development is governed by growing degree-days and daylength. Daily plant growth is computed by converting daily intercepted photosynthetically active radiation into plant dry matter using a crop-specific radiation use efficiency parameter, which is modified by water and nitrogen stress and temperature. Kernel numbers per plant are computed during flowering based on the cultivar's genetic potential number, biomass, rate of carbohydrate accumulation during flowering, and temperature, water and nitrogen stresses. The daily grain growth rate is calculated based on the potential kernel growth rate, which is modified by temperature and assimilate availability.

The soil water module is a one-dimensional model which computes the daily changes in soil water content by soil layer due to infiltration, drainage, unsaturated flow and evapotranspiration (Jones and Ritchie 1991; Ritchie 1998). Drainage is first calculated based on a soil drainage parameter. The amount of water passing through any layer is then compared with the saturated hydraulic conductivity of that layer. If the saturated hydraulic conductivity of any layer is less than the computed vertical drainage through that layer, actual drainage is limited to the conductivity value, and water accumulates above that layer (Williams et al. 1984). The soil-plant-atmosphere module brings together soil, plant and atmospheric inputs and computes light interception by the canopy, potential evapotranspiration, actual soil evaporation and plant transpiration. The potential evapotranspiration can be calculated by three different methods: Priestley-Taylor (Priestley and Taylor 1972) modified by Ritchie (1985), Penman-FAO24 (Jensen et al. 1990) and Penman-Monteith reference method (FAO56) (Monteith 1973; Allen et al. 1998). After comparing many models the FAO and International Commission on Irrigation and Drainage working groups recently recommended using FAO56 (Allen et al. 1998). Many studies indicated that FAO56 was better than the other two modules for calculating evapotranspiration and resulted in better simulations of biomass and yield (Jamieson et al. 1998; Ines et al. 2001; Irmak et al. 2003a, b; Sau et al. 2004; López-Cedrón et al. 2008; Yin et al. 2008). We, therefore, chose the FAO56 option for calculating potential evapotranspiration. Actual soil evaporation is based on a two-stage process. After the soil surface is first wetted due to either rainfall or irrigation, evaporation occurs at the potential rate until a cumulative soil evaporation amount since wetting is reached. Then, a soil-limiting daily soil evaporation amount is computed as a square root function of time. To determine whether the soil or atmosphere limits plant transpiration, potential root

Table 4. Comparisons between measured and simulated above-ground biomass and grain yield by Pearson correlation coefficient (*r*), concordance correlation (CCC), and *F* test for the lack of fit [*F*(LOFIT)]

Rotation	Measured	Simulated by DSSAT-CSM	*r*	CCC	*F*(LOFIT)[z]	*n*[y]
	(t ha^{-1})					
Biomass						
Continuous wheat	6.0	7.4	0.918***	0.703	0.018	9
Wheat-fallow	8.5	11.8	0.825**	0.529	0.021	9
Wheat-wheat-fallow	7.8	9.8	0.806***	0.588	0.020	18
Total	7.5	9.7	0.847***	0.620	0.013	36
Yield						
Continuous wheat	2.4	2.5	0.949***	0.877	0.014	9
Wheat-fallow	3.1	4.1	0.708*	0.483	0.046	9
Wheat-wheat-fallow	2.8	3.4	0.834***	0.683	0.018	18
Total	2.8	3.4	0.846***	0.692	0.009	36

[z]All *F* values for the lack of fit *F*(LOFIT) were significantly lower than the errors of measurements at $P < 0.05$.
[y]n = number of years × number of phases
*, **, *** Significant at 0.05, 0.01 and 0.001 probability level, respectively.

water uptake is computed by calculating a maximum water flow to roots in each layer and summing these values (Jones and Ritchie 1991). The actual plant transpiration is then computed as the minimum of potential plant transpiration and the potential root water uptake. The ratio of actual evapotranspiration to potential evapotranspiration is used in the plant modules to reduce photosynthesis in proportion to relative decreases in transpiration. The ratio of potential root water uptake and potential transpiration is used to reduce plant turgor and expansive growth of crops. These modules were described in more detail by Jones et al. (2003). Root growth and depth were simulated by a series of factors and parameters, such as potential root water uptake, root restriction factor, assimilation, assimilation partitioning, carbon allocation and root biomass/root length ratio (Jamieson et al. 1998).

Modification, Calibration and Simulations

The DSSAT-CSM model simulates cereal crop seedling emergence using thermal time, which is adjusted by a soil water factor, assuming that the adjusted thermal time is linearly related to the emergence process (Ritchie 1991). However, Jame and Cutforth (2004) indicated that the response of emergence to temperature is not linear. In order to improve the prediction we used the Beta model developed by Jame and Cutforth (2004) and validated by Wang et al. (2009) to simulate the date of seedling emergence of wheat. Phenology parameters for AC Barrie were calibrated using the observed data from a 4-yr (1998–2001) field study on a Swinton loam soil (Orthic Brown Chernozem) near Swift Current, SK (Wang et al. 2002, 2007b). Daily maximum and minimum air temperature, dew-point temperature, wind run and precipitation were obtained from the weather station located on the research site (Environment Canada 2008). Winter precipitation events were often not accurately recorded or missing. Missing data are replaced by records from the Three Hills South weather station (lat. 51°41'N, long. 113°19'W, elevation 846 m), but these may not accurately reflect the precipitation at the research site. Daily solar radiation was calculated using the Mountain Climate Simulator (Thornton et al. 2000).

Soil organic carbon, bulk density and fractions of sand, silt and clay at depths of 0 to 5, 5 to 15, 15 to 30, 30 to 45, 45 to 60, 60 to 90, 90 to 120, 120 to 150, 150 to 180 and 180 to 210 cm are calculated based on observation (Table 1) using linear interpolation and setting values for depths lower than 110 cm equal to the 80–110 cm layer. The lower limit of soil water availability, drained upper limit, saturated hydraulic conductivity and saturated volumetric moisture content were calculated according to Saxton et al. (1986) except that the

Table 5. Measured and simulated surface residue in the fall of 2006

Rotation	Phase in 2006	Measured	Simulated by DSSAT-CSM
		(t ha^{-1})	
Continuous wheat	Wheat	3.8 (0.3)[z]	4.5
Wheat-fallow-1	Wheat	4.2 (1.1)	6.6
Wheat-wheat-fallow-2	First year of wheat	5.1 (2.8)	6.4
Wheat-wheat-fallow-3	Second year of wheat	6.5 (2.0)	4.7

[z]The numbers in parentheses are standard errors.

Table 6. Assessments for simulations of soil water content at 0–6 cm measured by the Theta probe under continuous wheat with DSSAT-CSM and SHAW by Pearson correlation coefficient (r), concordance correlation (CCC), and F test for the lack of fit [F(LOFIT)]

Model	r	CCC	F(LOFIT)[z]
2001 (n = 23)			
DSSAT-CSM	0.944****a*	0.853*a*	0.007
SHAW	0.965****a*	0.927*a*	0.002
2002 (n = 21)			
DSSAT-CSM	0.485**a*	0.230*a*	0.027
SHAW	0.444**a*	0.389*a*	0.005
2003 (n = 17)			
DSSAT-CSM	0.636***a*	0.382*a*	0.026
SHAW	0.767****a*	0.736*a*	0.006
2004 (n = 25)			
DSSAT-CSM	0.762****a*	0.197*a*	0.028
SHAW	0.757****a*	0.326*a*	0.008
2005 (n = 28)			
DSSAT-CSM	0.226**a*	0.052*a*	0.030
SHAW	0.498***a*	0.258*a*	0.006
All (n = 114)			
DSSAT-CSM	0.492****b*	0.254*b*	0.006
SHAW	0.723****a*	0.602*a*	0.001

[z]All F values for the lack of fit F(LOFIT) were significantly lower than the errors of measurements at $P < 0.05$.
a, b Within columns and year, values followed by the same letter are not significantly different at the 0.05 level of probability according to Zar (1999).
*, **, *** Significant at 0.05, 0.01 and 0.001 probability level, respectively.

lower limit of soil water availability in the top layer (0–5 cm) was set to air dry soil water content because water loss can occur through evaporation from the soil surface until the soil is air dry (Penning de Vries et al. 1989). The air dry soil water content is estimated as 30% of the lower limit (Campbell and Stöckle 1993). The soil pH in water suspensions (pH_w) was calculated from the pH measured using calcium chloride solution (pH_{ca}) by the following equation according to Little (1992):

$$pH_w = 1.017\ pH_{ca} + 1.02 \tag{1}$$

Initial soil conditions are unknown in this study. Simulations using varying initial conditions of soil moisture and temperature showed that after 2 years' simulation, simulated soil temperature and moisture became independent of initial conditions. Therefore, simulations started 2 yr prior to the years with soil moisture observations.

Canopy information for SHAW

The SHAW model requires canopy information including height, characteristic dimension of leaves (leaf width, centimetre), dry biomass, leaf area index and rooting depth. The source code of DSSAT-CSM was modified to create an output file for daily canopy information. All parameters were simulated by DSSAT-CSM, except that the leaf width was calculated using an empirical equation ($r^2 = 0.98$, $n = 15$) based on measurements for AC Barrie in a field study at the Semiarid Prairie Agricultural Research Centre, Swift Current, SK (Wang et al. 2002):

$$\text{Leaf width} = 0.167\text{LN} + 0.24 \tag{2}$$

where LN is main stem leaf number.

Residue information for SHAW

The SHAW model requires information on soil surface residue, including total dry weight (t ha^{-1}), surface coverage (fraction 0–1) and thickness (cm). The DSSAT-CSM (Version 4.0) includes a soil organic matter decomposition and mineralization option based on the CENTURY SOM model (Gijsman et al. 2002). Using this option the dynamics of soil surface residue amount under the effect of tillage, weather and non-grain biomass production and rotation were simulated.

Steiner et al. (2000) measured residue dry weight and surface coverage seven times over the period of 14 mo for several crops in Mississippi and calculated cover coefficients (k, ha t^{-1}) using an exponential equation developed by Gregory (1982):

$$\text{Surface coverage} = 1 - \exp^{-k(\text{Ash-free dry weight})} \tag{3}$$

They found that the k value for spring wheat was weakly affected by time ($P < 0.3$). Therefore, we used the k value obtained from data of all sampling dates (1.71 ha t^{-1}, $P < 0.001$, $n = 187$) to calculate surface coverage using Eq. 3. Ash-free dry weight was calculated from simulated residue dry weight assuming the ash content is 11% (Radiotis et al. 1996).

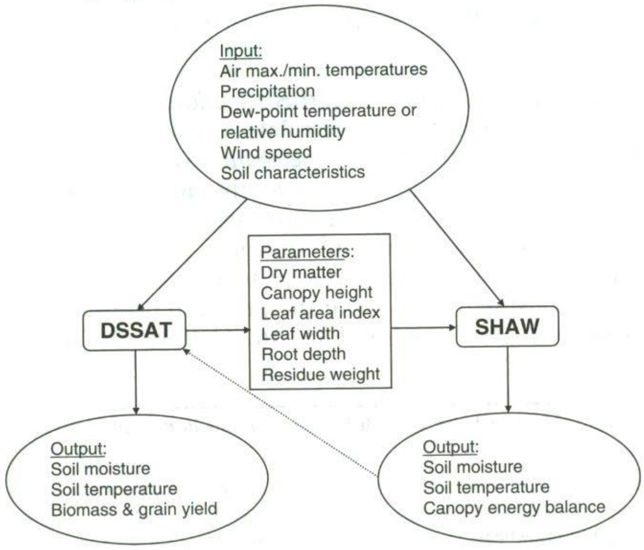

Fig. 1. Coupling scheme between DSSAT-CSM and SHAW models. The dotted arrow indicates future two-way coupling work if predictions of soil moisture and temperature are improved.

Table 7. Assessments for simulations of soil water content at 0–6 cm measured by the Theta probe under wheat-fallow rotations with DSSAT-CSM and SHAW by Pearson correlation coefficient (*r*), concordance correlation (CCC), and *F* test for the lack of fit [*F*(LOFIT)]

	Wheat-fallow-1 (the phase in 1992 was wheat)			Wheat-fallow-2 (the phase in 1992 was fallow)		
Model	*r*	CCC	*F*(LOFIT)[z]	*r*	CCC	*F*(LOFIT)[z]
2001 (n = 23)						
DSSAT-CSM	0.695****a*	0.505*b*	0.014	0.974****a*	0.903*a*	0.005
SHAW	0.875****a*	0.813*a*	0.003	0.953****a*	0.886*a*	0.003
2002 (n = 21)						
DSSAT-CSM	0.728****a*	0.342*a*	0.018	0.206*a*	0.068*a*	0.031
SHAW	0.849****a*	0.515*a*	0.006	0.226*a*	0.150*a*	0.006
2003 (n = 17)						
DSSAT-CSM	0.441*a*	0.396*a*	0.009	0.651****a*	0.428*a*	0.023
SHAW	0.773****a*	0.653*a*	0.006	0.778****a*	0.756*a*	0.005
2004 (n = 25)						
DSSAT-CSM	0.758****a*	0.507*a*	0.007	0.593***a*	0.129*a*	0.024
SHAW	0.741****a*	0.536*a*	0.004	0.661****a*	0.321*a*	0.005
2005 (n = 28)						
DSSAT-CSM	−0.141*a*	0.016*a*	0.025	0.390**a*	0.241*a*	0.010
SHAW	0.221*a*	0.120*a*	0.004	0.456**a*	0.363*a*	0.004
All (n = 114)						
DSSAT-CSM	0.329**b*	0.206*b*	0.004	0.569****a*	0.358*b*	0.004
SHAW	0.669****a*	0.571*a*	0.001	0.714****a*	0.634*a*	0.001

[z]All *F* values for the lack of fit *F*(LOFIT) were significantly lower than the errors of measurements at $P < 0.05$.
a, *b* Within columns and year, values followed by the same letter are not significantly different at the 0.05 level of probability according to Zar (1999).
*, **, *** Significant at 0.05, 0.01 and 0.001 probability level, respectively.

The thickness of residue layer (cm) was calculated using the following equation (Farahani and DeCoursey 2000):

$$\text{Thickness} = 10\text{Dry weight}/[\text{Coverage}\,(1-\phi_r)\rho_{sr}] \quad (4)$$

where ϕ_r is residue porosity (0.85; Farahani and DeCoursey 2000) and ρ_{sr} is specific density of wheat residue (170 kg m^{-3}; Unger and Parker 1976). The source code was also modified to create an output file for dynamics of soil surface residue.

The SHAW Model

Model Description

The SHAW model, originally developed to simulate soil freezing and thawing (Flerchinger and Saxton 1989), simulates heat, water and solute transfer within a one-dimensional profile which includes the effects of plant cover, dead plant residue and snow. This model has the ability to predict climate and management effects on soil freezing, snowmelt, runoff, soil temperature, water, evaporation, and transpiration. The advantages of the SHAW model in comparison with the soil water and temperature modules of DSSAT-CSM include: full solution of the surface energy balance; Richards equation solution for soil water redistribution rather than a "tipping bucket" approach; Green-Ampt infiltration rather than SCS curve number; and detailed winter routines (Flerchinger and Pierson 1991; Flerchinger et al. 1994; Hayhoe 1994; DeGaetano et al. 2001; Preston and McBride 2004; Huang and Gallich 2006; Fallow et al. 2007).

Weather conditions above the upper boundary and soil conditions at the lower boundary define heat and water fluxes into the system. Water and heat flux at the surface boundary include absorbed solar radiation, long-wave radiation exchange, and turbulent transfer of heat and vapour. After computing flux at the upper boundary, the inter-related heat, liquid water and vapour fluxes between layers are determined. Transpiration from plants is linked mechanistically to soil water by flow through the roots and leaves. Plant water uptake and transpiration is determined assuming a soil-plant-atmosphere continuum and calculated from the water potential in the soil, through the roots, to the water potential in the plant xylem; from there to the leaf water potential; and from stomatal cavities in the leaves through the stomates to the ambient air within the plant canopy. Evaporation from the soil or residue surface is computed directly from the gradient in vapour density between the surface and the bottom canopy node. Water uptake, transpiration and leaf temperature are coupled through the energy balance of the leaf and include net solar and long-wave radiation, latent heat of vaporization associated with transpiration, and convective heat transfer, respectively, within the canopy layer. Details for calculating components of the energy balance for each plant species are given by Flerchinger and Pierson (1991).

Simulations

Soil nodes at depths of 0, 1 to 15 cm (1 cm interval), 17 to 37 cm (2 cm interval), 40 to 70 cm (5 cm interval), 80 to 100 cm (10 cm interval), 120 to 200 cm (20 cm interval), 300, and 400 cm were simulated by SHAW. For each soil layer, bulk density and fractions of sand, silt and clay were estimated based on the information in a manner similar to that for DSSAT-CSM.

Soil hydraulic parameters including pore-size distribution index, air-entry potential, saturated hydraulic conductivity and saturated volumetric moisture content for each soil layer were calculated based on the information of Table 1 using the SHAW model user interface, ModShell (Flerchinger 2000). The interface uses relations based on Saxton et al. (1986). Similar to the application of DSSAT-CSM, the pore-size distribution index at layers above 6 cm was adjusted (reduced) to allow the lowest near-surface soil volumetric water content to be as low as air dry (30% of the lower limit; Campbell and Stöckle 1993). Soil organic carbon was converted to soil organic matter by multiplying by a factor of 1.72 (Nelson and Sommers 1996).

The SHAW model requires a daily weather file which includes maximum and minimum air temperature, dew-point temperature, total wind run, precipitation and solar radiation. All weather data were obtained from a weather station located adjacent to the research plots except that daily solar radiations were calculated using the Mountain Climate Simulator (Thornton et al. 2000). Similar to DSSAT-CSM, in order to minimize the effect of initial conditions of soil moisture and temperature, simulations started 2 yr prior to the years with soil moisture observations. The source code was modified to use soil surface residue dynamics, which was provided by DSSAT-CSM, instead of constants.

Table 8. Assessments for simulations of soil water content at different depths and total water at 0–120 cm measured by gravimetric method under continuous wheat with DSSAT-CSM and SHAW by Pearson's correlation (*r*), concordance correlation (CCC), and *F* test for the lack of fit [*F*(LOFIT)]

Model	*r*	CCC	*F*(LOFIT)[z]
Water content 0–15 cm (n = 22)			
DSSAT–CSM	0.493**a*	0.179*a*	0.018
SHAW	0.672****a*	0.324*a*	0.010
15–30 cm (n = 11)			
DSSAT-CSM	0.547*a*	0.155*a*	0.021
SHAW	0.723**a*	0.340*a*	0.015
30–60 cm (n = 11)			
DSSAT-CSM	0.561*a*	0.194*b*	0.016
SHAW	0.787***a*	0.716*a*	0.004
60–90 cm (n = 11)			
DSSAT-CSM	0.595*a*	0.174*b*	0.012
SHAW	0.820***a*	0.689*a*	0.003
90–120 cm (n = 11)			
DSSAT-CSM	0.205*a*	0.020*a*	0.062
SHAW	0.608**a*	0.308*a*	0.005
Total water 0–120 cm (n = 11)			
DSSAT-CSM	0.639**a*	0.297*a*	0.005
SHAW	0.813***a*	0.494*a*	0.005

[z]All *F* values for the lack of fit *F*(LOFIT) were significantly lower than the errors of measurements at $P < 0.05$

a, b Within columns and depth, values followed by the same letter are not significantly different at the 0.05 level of probability according to Zar (1999).

*, **, *** Significant at 0.05, 0.01 and 0.001 probability level, respectively.

Model Sensitivity

The relative importance of parameters simulated by DSSAT-CSM on the prediction of soil moisture by SHAW was assessed by running SHAW for the period of day 110–250, 2001 under conventionally tilled continuous wheat repeatedly, by varying each parameter with three equally spaced intervals between low and high values (0–2m for canopy height, 0–2 cm for leaf width, 0–1 kg m^{-2} for canopy biomass, 0–7 for leaf area index, 0 to 1.5 m for rooting depth, 0 to 20 t ha^{-1} for surface residue weight, 0–0.99 for residue coverage, and 0–7 cm for residue thickness). Effects of parameters and their interactions were analyzed by PROC MIXED in SAS software (SAS Institute, Inc. 1996), assuming that the higher order interactions are negligible (Lurette et al. 2009). Data were analysed using the first-order autoregressive covariance structure with day treated as repeated measures. To understand the cause-and-effect interrelationships between these parameters and simulated soil moisture under real environments, the SHAW model was run using 48 pairs of DSSAT 10-years' growth and residue outputs, which were created by varying fertilizer rate, irrigation, rotation and tillage. Path analyses were conducted to separate direct and indirect effects of these parameters on soil moisture (Alwin and Hauser 1975). The 95% confidence intervals of direct effects were calculated from 1000 bootstrap resampling data sets (Efron and Gong 1983) using BC method (Efron 1981).

Model Coupling

The coupling scheme between DSSAT-CSM and SHAW was shown in Fig. 1. The two models require the same inputs of weather and soil data. The modified DSSAT-CSM was run first to create canopy and surface residue output files. Then, the modified SHAW model was run using the option to read the canopy file and using the residue dynamics provided by DSSAT-CSM. Both models have outputs of soil moisture and temperature. If this approach could improve the prediction of both soil moisture and temperature by SHAW, a two-way coupling work between DSSAT-CSM and SHAW will be implemented in the future (Fig. 1).

Model Evaluation and Comparison

Simulation results were compared with observations using Pearson's correlation (Draper and Smith 1966), concordance correlation (Lin 2000) and the lack of fit test (Whitmore 1991). The Pearson's correlation coefficient (*r*) does not assess goodness of fit, but evaluates the association between simulated and measured values (precision). If the *r* value is significantly high it may indicate that the structure of the model is appropriate (Smith et al. 1996). The concordance correlation coefficient (CCC) reflects the degree to which individual predictions adhere to the concordance line, which is an indicator for both precision and accuracy. Values of CCC close to one indicate that there is good agreement between measurements and simulations. The significances of difference in r and CCC between two models were compared according to Zar (1999). The lack of fit tests systemic errors, which allows the experimental errors to be distinguished from the failure of the model (Whitmore 1991). The statistical significance of lack of fit was obtained by comparing the F value for the lack of fit [F (LOFIT)] with the F critical values at the 0.05 probability level ($F_{0.05}$) (Smith et al. 1997). If F (LOFIT) is higher than $F_{0.05}$ it indicates the error in the simulated values was significantly greater than the error inherent in the measured values.

RESULTS AND DISCUSSION

Sensitivity

Statistical analysis showed that although many parameters had significant impacts on simulated soil moisture the most important parameters were residue thickness, root depth and leaf area index ($P<0.001$). Biomass and its interactions with other parameters had no effects (F = 0). The residue thickness had relatively higher effects on near-surface moisture than on the deeper depths. The effect of root depth was increased at deeper depths. Leaf area index consistently had a significant effect over the soil depth ($P<0.001$). Although there are some interactions between parameters, generally there were no crossover interactions. For example, the increase of residue thickness increased soil moisture regardless of leaf area index, but when leaf area index was high the increase in soil moisture was less than when the leaf area index was low (data not shown). Dynamic changes of some parameters, such as leaf area and root depth, are often confounded with each other. Therefore, their effects on soil moisture are combinations of direct and indirect effects. Root depth was the most influential character on soil moisture with both high negative direct and total effects (Table 3). The total effect of leaf area index on soil moisture was significant at all the soil depths, but mainly via its indirect effect on root depth because there is a close correlation between leaf area index and root depth ($P<0.001$). The negative effects of leaf area and root depth were reduced by their effects on residue thickness because biomass production is slightly associated with surface residue ($P<0.05$). Although the total effect of residue thickness was not high except on near-surface soil moisture, its direct effect was substantial. Surface residue parameters are actually not necessarily associated with plant growth because it is mainly determined by tillage and can be added on the soil from other sources. Therefore, residue thickness is always an important factor, especially on near-surface moisture.

Weather Conditions

Over the 10 yr (1997 to 2006), annual mean air temperatures were consistently higher than the long-term (1924 to 2006) average (2.4°C), but precipitation was lower than the average (366 mm) in most of the

Table 9. Assessments for simulations of soil water content at different depths and total water at 0–120 cm measured by gravimetric method under wheat-fallow rotations with DSSAT-CSM and SHAW Pearson's correlation (r), concordance correlation (CCC), and F test for the lack of fit [F(LOFIT)]

	Wheat-fallow-1 (the phase in 1992 was wheat)			Wheat-fallow-2 (the phase in 1992 was fallow)		
Model	r	CCC	F(LOFIT)[z]	r	CCC	F(LOFIT)[z]
Water content 0–15 cm (n = 22)						
DSSAT-CSM	0.497**a*	0.266*a*	0.011	0.401*a*	0.182*a*	0.013
SHAW	0.757****a*	0.445*a*	0.007	0.384*a*	0.233*a*	0.007
15–30 cm (n = 11)						
DSSAT-CSM	0.577*a*	0.187*a*	0.018	0.659**a*	0.148*a*	0.021
SHAW	0.705**a*	0.271*a*	0.015	0.658**a*	0.187*a*	0.017
30–60 cm (n = 11)						
DSSAT-CSM	0.696**a*	0.215*b*	0.018	0.586*a*	0.179*b*	0.018
SHAW	0.793***a*	0.781*a*	0.002	0.697**a*	0.689*a*	0.003
60–90 cm (n = 11)						
DSSAT-CSM	0.448*a*	0.068*b*	0.026	0.795***a*	0.139*a*	0.028
SHAW	0.634**a*	0.599*ab*	0.004	0.550*a*	0.463*a*	0.006
90–120 cm (n = 11)						
DSSAT-CSM	0.074*a*	0.001*b*	0.128	0.787***a*	0.014*a*	0.188
SHAW	0.730***a*	0.619*a*	0.002	0.214*a*	0.108*a*	0.015
Total water 0–120 cm (n = 11)						
DSSAT-CSM	0.565*a*	0.165*b*	0.014	0.647**a*	0.179*a*	0.013
SHAW	0.812****a*	0.771*a*	0.002	0.588*a*	0.579*a*	0.003

[z]All F values for the lack of fit F(LOFIT) were significantly lower than the errors of measurements at $P<0.05$.
a, b Within columns and depth, values followed by the same letter are not significantly different at the 0.05 level of probability according to Zar (1999).
*, **, *** Significant at 0.05, 0.01 and 0.001 probability level, respectively.

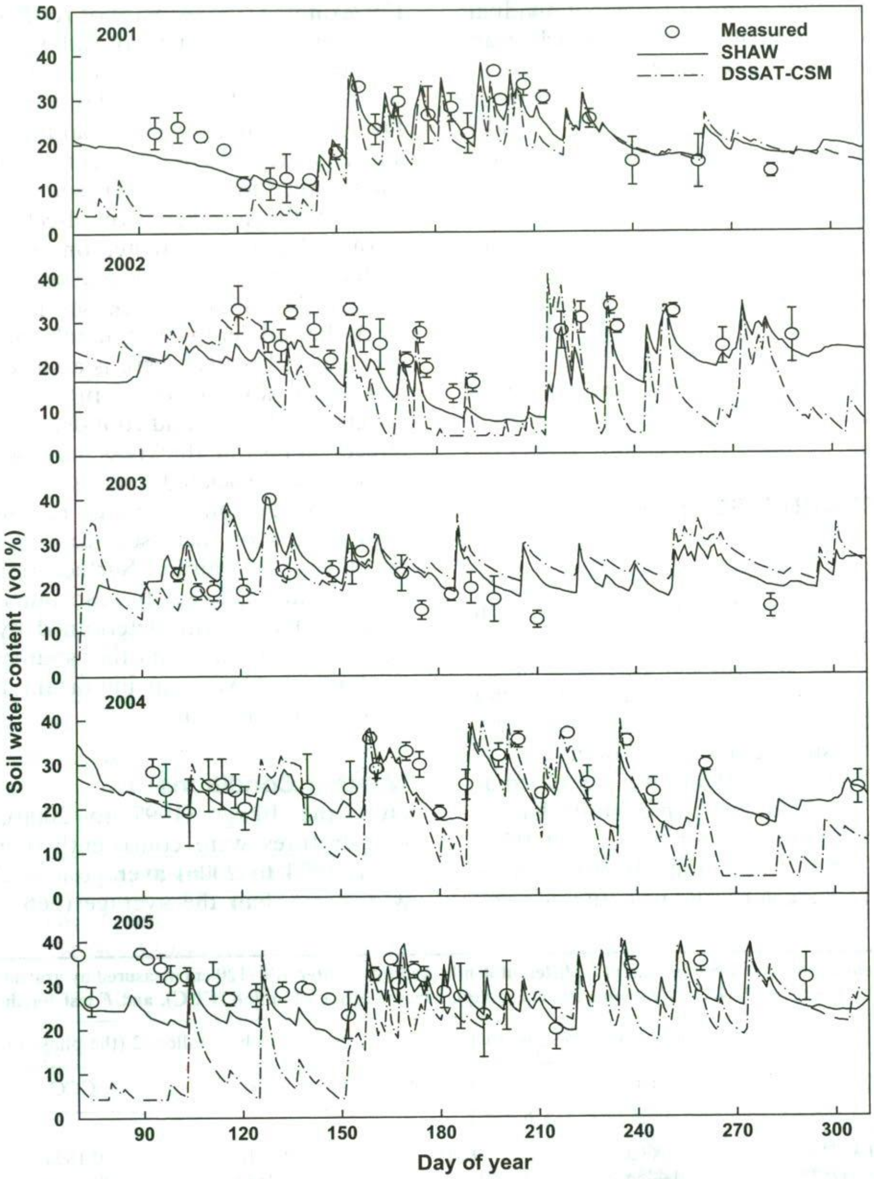

Fig. 2. Soil water contents simulated at 0–5 cm by DSSAT-CSM and at 0–6 cm by SHAW and observed at 0–6 cm using Theta probe in the conventionally tilled continuous wheat at Three Hills, AB. Vertical bars represent the standard error.

years (data not shown). In 2002, precipitaition during growing season (May to July) was very low (118 mm) compared with the long-term average (172 mm) and air temperatures in June (15.9°C) and July (18.9°C) were very high, which resulted in extremely low yield and biomass. In 2003, although it was also dry during the growing season (117 mm), the temperature was not as high as that recorded in 2002 (14.5°C in June and 17.9°C in July), therefore, yield reduction was less than in 2002.

Simulated Parameters by DSSAT-CSM

We were not able to assess simulations of detailed canopy and surface residue dynamics by DSSAT-CSM except harvested above-ground biomass at full maturity from 1998 to 2006 and surface residue collected in the fall of 2006. Simulated above-ground biomass was higher than measurements (Table 4). This is partially due to sampling occurring at full maturity, which was about 10–20 days after physiological maturity when the wheat reached its maximum biomass. Some senescent leaves, ripened spikes and broken tillers fall to the ground during this period, and are difficult to recover. Another reason is that the model is based on the assumption that weeds, disease or insects do not affect growth or yield. Thus, the DSSAT-CSM model actually simulates an upper limit of crop production under the

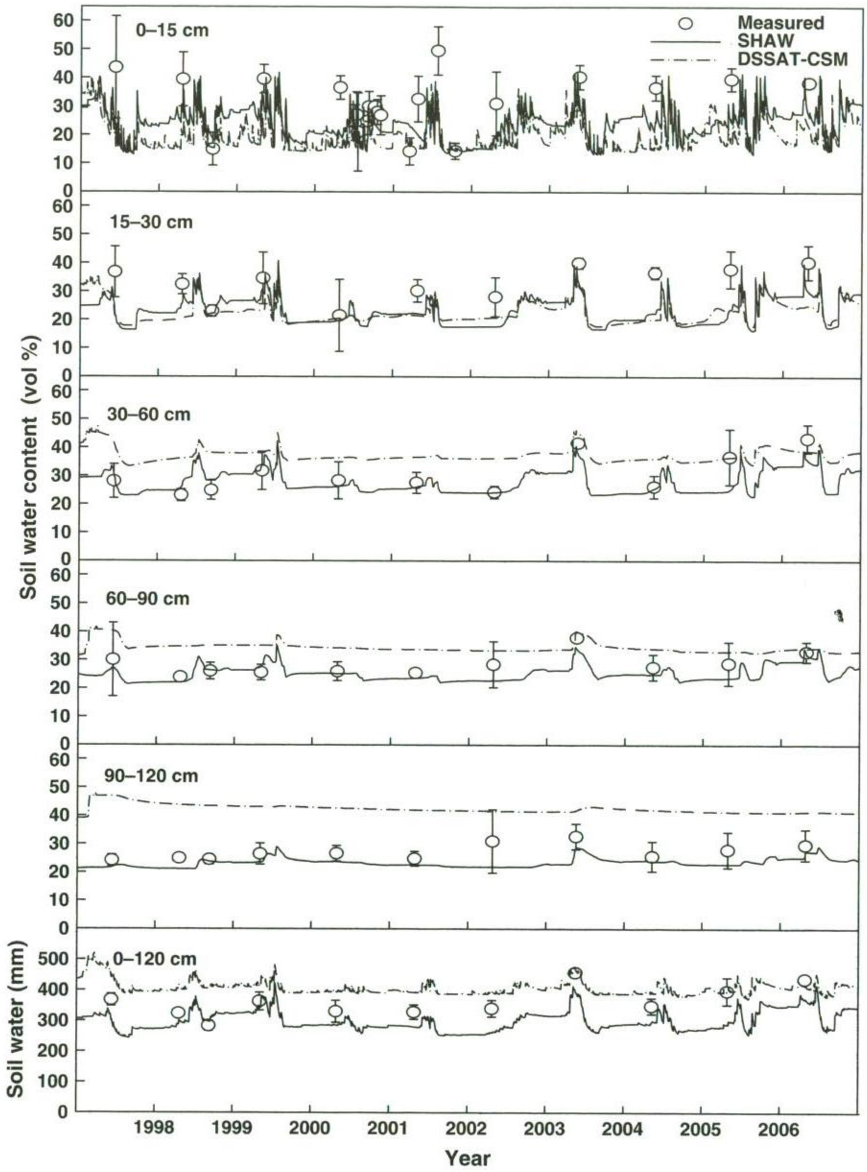

Fig. 3. Soil water contents at 0–15, 15–30, 30–60, 60–90 and 90–120 cm and total water at 0–120 cm simulated by DSSAT-CSM and SHAW and observed by gravimetric method in the conventionally tilled continuous wheat at Three Hills, AB. Vertical bars represent the standard error.

management and environment (Rosenzweig et al. 1999; Quiring and Legates 2008). In reality, all of the above reduce yield to some extent on the Canadian prairies (Holmes 1977; O'Donovan et al. 2005; Manitoba Agriculture, Food and Rural Initiatives 2006; Beres et al. 2007). Wheat yield loss due to pests (e.g., wheat stem sawfly and grasshopper) and diseases (e.g., leaf spot and common root rot) is estimated to be about 20% each year in this region (Galushko and Gray 2008). Although simulated grain yield was also higher than measurements, the overestimation averaged 10% less than biomass. Obviously, the yield loss caused by the late sampling would be less compared with the loss of biomass. Although the harvested biomass and yield could be markedly reduced by weed, disease and/or insect pressures, the magnitude of the reduction in canopy development such as height and leaf thickness could be less.

There were significant Pearson's correlations between simulation and measurement in biomass and yield under different rotations (Table 4). This indicates that the structure of the DSSAT-CSM model is sound for modeling wheat growth. The concordance correlation coefficients ranged from 0.53 to 0.70 for biomass and 0.48 to 0.88 for yield, indicating certain agreement between measurements and simulations. Simulated biomass and

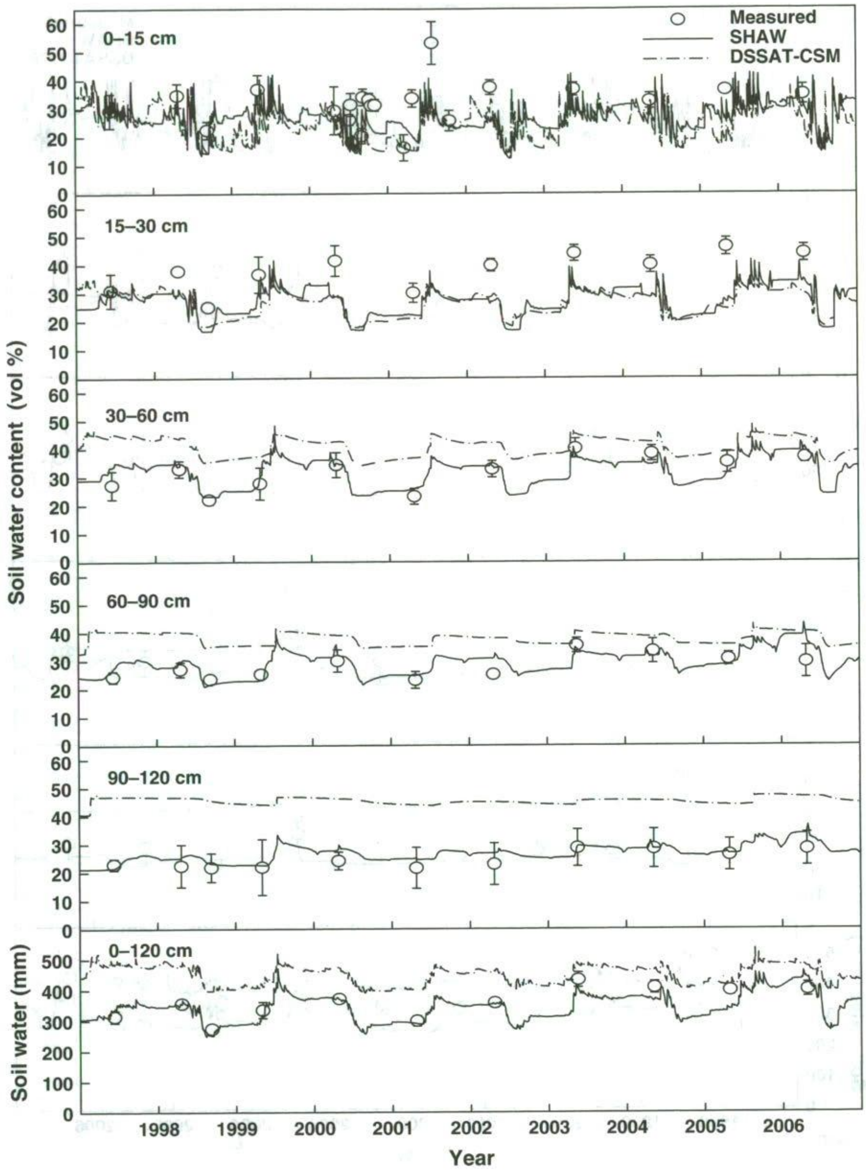

Fig. 4. Soil water contents at 0–15, 15–30, 30–60, 60–90 and 90–120 cm and total water at 0–120 cm simulated by DSSAT-CSM and SHAW and observed by gravimetric method in the conventionally tilled wheat-fallow rotation with the wheat phase stared in 1992 at Three Hills, AB. Vertical bars represent the standard error.

yield for all rotations were not significantly different from measured values by LOFIT test (F (LOFIT) $< F_{0.05}$). Although SHAW-simulated soil moisture is not sensitive to the biomass dynamics, the dynamics of leaf area index is usually positively related to the dynamics of biomass before anthesis completion (Wang and McCaig, unpublished data).

The DSSAT-CSM model simulated surface residue reasonably well (Table 5), the F value for the lack of fit F(LOFIT) of crop residue over all rotations was 0.06, which indicated that the error inherent in the simulation was much lower than experimental error ($F_{0.05} = 3.44$).

Soil Moisture Simulated by DSSAT-CSM and SHAW

Near-surface Moisture Measured by Theta Probe

Measured soil water content at 0–6 cm by the Theta probe under continuous wheat was positively correlated ($P < 0.05$) with simulated values over the years for each model, but SHAW consistently had higher CCC than DSSAT-CSM (Table 6). For each year, simulated values by DSSAT-CSM are often lower compared with measurements (Fig. 2). The error for simulations of near-surface soil moisture for both SHAW and DSSAT-CSM were significantly lower than the experimental error,

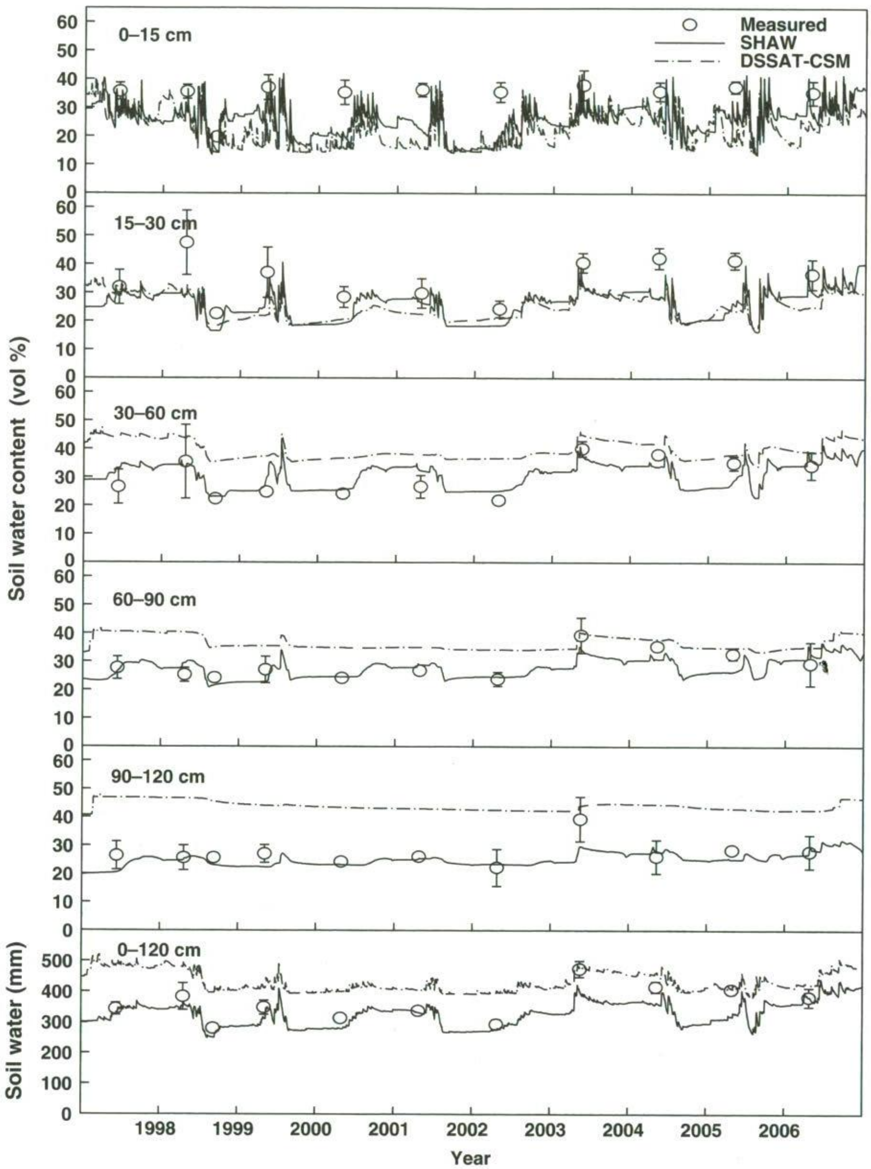

Fig. 5. Soil water contents at 0–15, 15–30, 30–60, 60–90 and 90–120 cm and total water at 0–120 cm simulated by DSSAT-CSM and SHAW and observed by gravimetric method in the conventionally tilled wheat-wheat-fallow rotation with the first wheat phase started in 1992 at Three Hills, AB. Vertical bars represent the standard error.

but SHAW consistently had lower *F* (LOFIT) than DSSAT-CSM (Table 6). Combined analyses of data over the 5 yr indicated that SHAW had significantly higher precision (*r*) and concordance (CCC) than DSSAT-CSM. Although SHAW improved simulation in terms of both value and trend for each year compared with DSSAT-CSM, it was not always satisfactory. For example, underestimation occurred in the early part of the seasons in 2004 and 2005 for all simulations (Fig. 2). The reason is not clear, but it might be related to the inaccuracy of precipitation records in the winters as stated above or the measurement errors. For example, in 2005 from day 74 to 89 (March 15 to 30), soil volumetric water content at 0–6 cm increased from 28.5 to 38.1% (6 mm), but the total recorded snow and rain during this period was only 3.1 mm. Caution should be used when comparing models for this depth because the first layer simulated by DSSAT-CSM was 0–5 cm instead of 0–6 cm.

Similar to continuous wheat, predicted soil water content was correlated with observations in most of the years for both models and in both phases (i.e., starting year of 1992 in wheat or fallow) of the wheat-fallow rotation (Table 7). However, the SHAW model consistently had higher CCC and lower *F* (LOFIT) than DSSAT-CSM. Combined analyses showed that SHAW had significantly ($P < 0.05$) higher CCC than DSSAT-CSM.

Gravimetrically Measured Soil Water

The DSSAT-CSM model often predicted soil moisture under continuous wheat unsatisfactorily with nonsignificant r and CCC (Table 8). In contrast to the near-surface depth, water content simulated by DSSAT-CSM changed less over time. DSSAT-CSM often overestimated water content from 30 to 120 cm and total water from 0 to 120 cm (Fig. 3). The SHAW model markedly increased r and CCC, indicating that it improved both precision and accuracy. Similar to the continuous wheat treatment, the SHAW model consistently had higher CCC and lower F (LOFIT) compared with DSSAT-CSM in simulated water content at each depth and total soil water at 0–120 cm in the wheat-fallow rotations (Table 9) and DSSAT-CSM over-predicted water content from 30 to 120 cm and total water in the 120 cm soil profile (Fig. 4). Prediction of soil water content by SHAW was improved relative to DSSAT-CSM in all depths of all phases of the wheat-wheat-fallow rotation, with higher correlation coefficient and CCC and lower F (LOFIT), especially during the two wheat phases (data not shown). Soil water content was overestimated in DSSAT-CSM at the three lower depths in the rotation of wheat-wheat-fallow-1 (Fig. 5, 1992 was the first year of wheat), which was reflected markedly by low CCC and F (LOFIT) when compared with those for SHAW. Similar results were observed in the other two phases (data not shown).

Results of all rotations are in agreement with the study of Hasegawa et al. (2000) in that DSSAT-CSM often overestimated the drying of the surface layers in wheat rotations. It is surprising that DSSAT-CSM consistently overestimated soil moisture in the deep soil for all rotations in this study considering that the model often estimated that the root system reached soil deeper than 80 cm (data not shown). De Farial and Bowen (2003) also found that DSSAT underestimated root water extraction from a dry bean field. The SHAW model improved the estimation of soil water content at all depths and total water at 0–120 cm in all wheat rotations and with all different phases by improving accuracy and precision.

Although sensitivities of canopy and residue parameters to the soil moisture simulation of SHAW were compared, their estimations by DSSAT-CSM were not evaluated because not enough observations were available, and therefore, the model uncertainty for simulating soil moisture was not determined, which should be investigated in further work.

CONCLUSION

Similar to previous studies DSSAT-CSM tended to overestimate the drying of the surface layer, and it also overestimated soil water content in the deeper depths (30–120 cm). It seems that DSSAT-CSM under-predicted root water uptake from the deeper soil although it often simulated rooting to greater than 80 cm. The DSSAT-CSM model, however, is able to provide reasonable canopy and surface residue information for SHAW, a more sophisticated, hourly time step soil microclimate model, to predict long-term soil moisture dynamics. The SHAW model improved estimation of soil water content at different depths and total water at 0–120 cm in all different wheat rotations and with different phases by improving accuracy and precision. Although sensitivities of canopy and residue parameters to the soil moisture simulation of SHAW were compared, their estimations by DSSAT-CSM were not evaluated because not enough observations were available, and therefore, the model uncertainty was not determined. Further work should be done to evaluate the confidence intervals of these DSSAT-CSM estimated parameters and the uncertainty of SHAW for predicting soil moisture under the effect of these parameters. Further work is also needed to test the prediction of soil temperature by SHAW in comparison to DSSAT-CSM simulations. If the SHAW model is superior to DSSAT-CSM in predicting both soil moisture and temperature, a two-way coupling between DSSAT-CSM and SHAW will be implemented, which could improve the simulation of DSSAT-CSM in growth, yield, N leaching, and other relevant processes.

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